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High-speed intensified camera system for investigation of plasma turbulence induced by the aurora

Semeter

Boston University

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Final Report

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High-speed intensified camera system for investigation of plasma turbulence induced by the aurora

Contract #: FA9550-11-1-0356

Final Report

Joshua Semeter, Boston University

1 Project overview

This is the final report for a one-year effort to develop a high frame-rate multi-scale camera for investigations of fine-scale auroral dynamics and induced beam-plasma instabilities in the high-latitude ionosphere. The instrument is referred to as the Deployable Multi-scale Camera, or DMC. The scope of the project included development and field-testing of the instrument, as well as development of an image processing framework for extracting physical parameters (such as spatial and temporal power spectra, coherence scales, and electron energy flux variability) from the recorded measurements. An innovative optical architecture was employed, consisting of a low-noise scientific-grade CMOS sensor coupled to a 140-mm f/1 optic through a prompt-emission notch filter. The resulting design provided meter-scale spatial resolution at 120-km stand-off distance over an 8x6 degree field-of-view. 16-bit sampling provided the large dynamic range required to observe the full range of variability in the aurora. A lower resolution wide-field sensor provided contextual information and the acquisition trigger for the CMOS sensor. Triggering was accomplished via real-time analysis of intensity and motions of targets within the field.

Initial observations from the Sondrestrom, Greenland, ionospheric research facility have provided compelling proof-of-concept in support of a broader science program, as discussed in this report.

2 Instrument Description

2.1 Optical design

The science requirements for the DMC called for a two-sensor architecture (Figure 1). A low-resolution wide-field camera (60° field of view) provided scientific context as well as the triggering signal for the narrow-field high-frame-rate camera (8° field of view). The frame rates, dynamic range, fields-of-view, and spatial resolution of these complementary sensors covers the full expected range of variability of the aurora in space, time, and luminosity. The DMC is arguably the first single-platform auroral sensor to achieve this objective.

The narrow-field camera employs a 140-mm f/1 optic and an optical notch filter coupled to a scientific-grade CMOS sensor. The notch filter was designed to reject metastable emissions of atomic oxygen (primarily 557.7nm and 630.0nm), providing an optical signal dominated by the prompt band systems of N_2 and N_2^+ . The scientific CMOS (sCMOS) camera was provided by Andor Technologies. This sensor provides a large pixel count (2560x2160) and a burst mode readout speed of 100 frames per second. The camera was mounted to a worm-driven translating table, which provided the focusing mechanism for the system, and the method by which optical filters may be inserted and removed.

The spatial resolution at full frame is 7 m referenced to a nominal auroral altitude of 120 km. This resolution exceeds expected spatial scales under observation, and thus 4x4 on-chip binning is employed which increases both the SNR and the available frame rate.

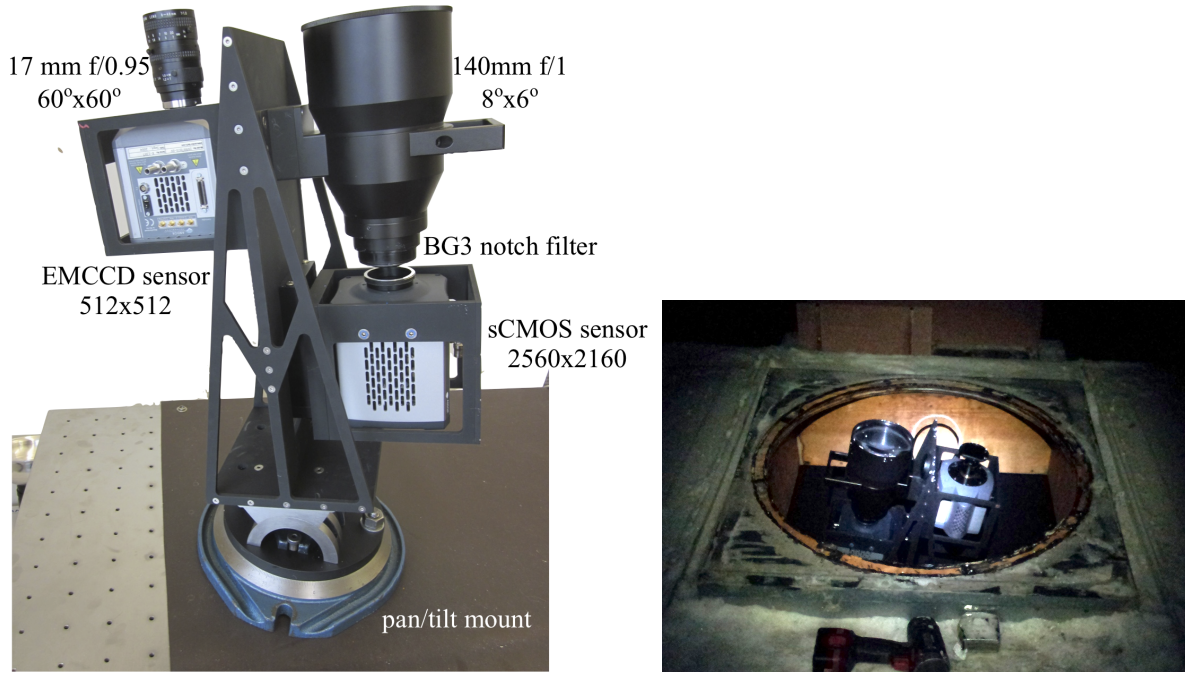


Figure 1: Left: DMC on the bench at Boston University, with principal elements labeled. Right: DMC during installation at the Sondrestrom research facility, December 2012. Because of the extremely narrow field of the DMC, the optical dome had to be replaced with a flat glass aperture. This infrastructure modification is one of the many ways in which the Sondrestrom crew contributed to the successful outcome of this project.

2.2 Data acquisition system

The data acquisition system consists of single computer running both cameras concurrently. The Windows-based system is accessible through a remote desktop connection. The computer motherboard is vPro capable, which allows full low-level control for remote recovery from catastrophic system failures. Data are initially stored on 10 Terabytes of integrated solid-state memory, and then off-loaded to external drives through the USB 3.0 port.

The data acquisition software is Labview-based, and communicates with the camera drivers through the Software Developers Kit (SDK) provided by the manufacturer. Numerous problems were encountered with the delivered SDK. These issues were addressed through many hours of interactions with the manufacturer. Problems were eventually resolved toward the end of December, 2012, which delayed first-light measurements of the full system to January 2013.

The max data rate for the CMOS sensor is 275Mb/s and therefore continuous recording for more than a few minutes is not feasible. The solution was to implement a continuous circular buffer for the CMOS sensor. When an auroral event is detected by the wide-field sensor, a trigger initiates dump of the CMOS buffer to memory, and continued recording for a prescribed period thereafter. In order to avoid anomalous triggering—by, e.g., clouds or man made light—the triggering decision

is based on real-time calculation of observed morphologies using the Lucas-Kanard optical flow estimation scheme. A GPS time stamp is recorded for each image.

Due to the large data files produced by the DMC, routine electronic transfer of raw data is not possible viable. Initial data review is conducted using time-brightness images along a cut through the magnetic zenith (so-called “keograms”), compressing long image sequences to a single 2D image. When an interesting event is identified, the corresponding image sequence is synthesized into highly compressed format (currently ogv) for transfer. Full data files for the first season of operations will be retrieved this summer.

3 First-light observations

The DMC was deployed to the NSF research facility at Sondrestrom, Greenland, in August 2012. The system software was still in beta phase at this point, but advantage was taken of the excellent technical support available at Sondrestrom to wring out remaining problems (some discussed above). Operations of the full system began in January 2013.

Figure 2 shows an example of a triggered acquisition acquired by the system on January 13, 2013. The left panel shows the contextual image acquired by the low resolution camera. The remaining numbered images (20-ms cadence) were acquired by the CMOS sensor, and illustrating the formation of parallel auroral forms of <200 -m width within a 100-ms interval (highlighted by the arrows in panel 4).

Figure 3 was recorded a few seconds later during the same auroral event. The field of view shown is 2.5° degrees, and corresponds to a region-of-interest subset of the full CMOS field. The region of interest is illustrated by dashed line in Figure 2, panel 4. The sequence of 11 images in Figure 3 illustrates the development of a multiple-arc “packet” during a 100-ms interval. The coherent phase structure within this packet can be detected as a subtle effect in panel 11, Although further image processing is needed, this is an exciting confirmation of the monochromatic nature of the physics governing the aurora at its finest scales, and provides proof-of-concept for the DMC project.

4 Planned Science Program

This 1-year effort was primarily focused on developing, deploying, and testing the DMC instrument. Initial observations from Sondrestrom have provided convincing proof-of-concept for this design. The objective of this project now turns to the science program. There are several specific science topics that may be pursued in this program. The initial emphasis, discussed also in the project justification described in the proposal, concerns wave-particle coupling in the near-Earth magnetosphere, and its causative connections to the development of ionospheric turbulence by auroral processes.

The project was motivated by observations of highly coherent variations in the fine-scale structure embedded within auroral arcs [Semeter and Blixt, 2006; Semeter *et al.*, 2008]. A plausible explanation for this dynamic invokes particle acceleration via dispersive Alfvén waves, but the evidence is far from complete. First, this type of dynamic has not been fully resolved by extant sensors. Second, it is not known to what extent this dynamic is scale-dependent. And finally,

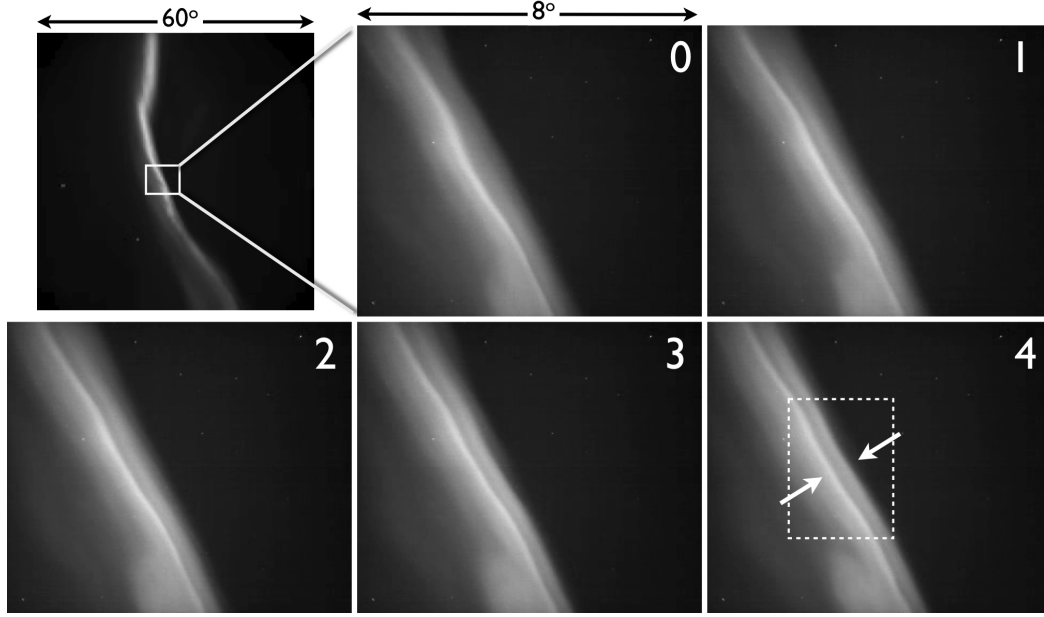


Figure 2: First observations of auroral dynamics recorded by the DMC on January 13, 2013. The upper right image was recorded with the wide-field sensor. The remaining enumerated images document the dynamics occurring within the 8x6 degree field of view of the CMOS sensor at 20-ms cadence. The sequence documents the formation of parallel auroral forms of 200-m width over a 100-ms interval.

coordinated observations with other sensors are needed to establish whether these features are related to structuring and wave propagation characteristics of the ionosphere.

Further progress in this research requires an amalgam of two discipline—image processing and space plasma physics. Specifically, in order to discuss how the observed dynamics should be mapped to the underlying M-I coupling, algorithmic approaches must be developed to extract and interpret space-time image plane morphologies. A framework for approaching this aspect of the research was published as an AGU monograph chapter under sponsorship of this project [Semeter, 2013]. The PI and his graduate students are adapting algorithms from the field of optical flow estimation in an effort to establish the physical properties of the magnetospheric wave field suggested by the observations exemplified in Figures 2 and 3.

In terms of scientific interpretation of such results, it is well established that field-aligned bursts of low energy electron precipitation occur at the edges of dynamic auroral forms. Incoherent Scatter Radar measurements have identified anomalous ionospheric turbulence in these regions [Akbari *et al.*, 2012]. A recent study, sponsored under this project, has revealed that this edge turbulence appears in thin layers at ranges where the ionospheric density gradients become 0 (F-region peak, and E-to-F region transition) [Akbari *et al.*, 2013]. Initial observations by the DMC have revealed a subtle optical signature in this region that appears as a damped outward propagating wave with wavelength $\sim 300\text{m}$ (Figure 3). Further image processing will quantify the parameters of this dynamic (e.g., k, ω spectrum); further accumulation of data will establish whether this is a consistent feature at auroral edges; and, finally, systematic comparison with space-borne and ground-based measurements will establish the electrodynamic context of these features and their consequences for communications, navigation, and high-latitude radar discrimination.

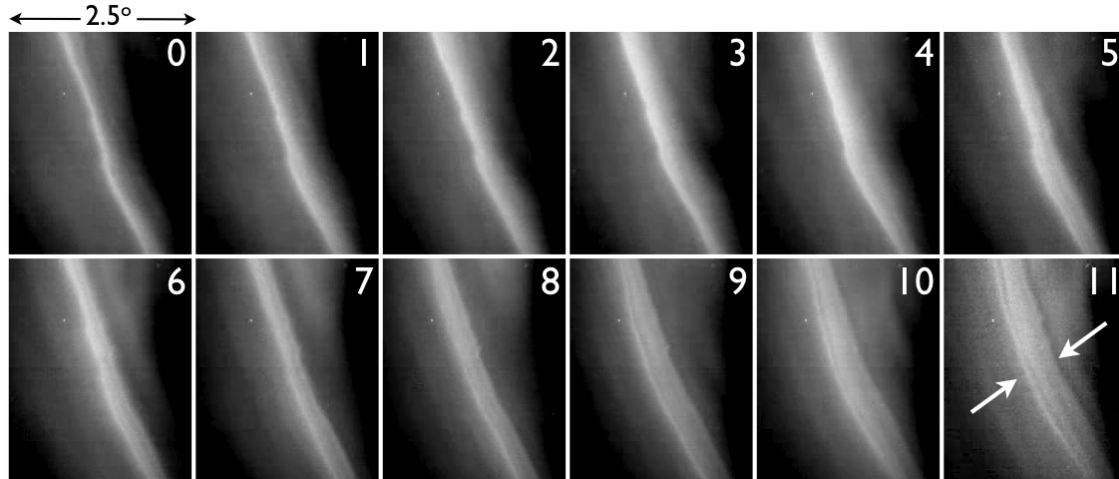


Figure 3: Example that pushes at the limits of space-time detectability. Formation of a multi-arc packet within a 2.5-degree field of view.

5 Archival Publications

Two publications have been produced thus far under sponsorship of this project:

Semeter, J., Coherence in Auroral Fine Structure, in *American Geophysical Union Geophysical Monograph Series*, vol. 197, edited by A. Keiling, E. Donovan, F. Bagenal, and T. Karlsson, pp. 8190, doi: 10.1029/2011GM001196, 2013.

Akbari, H., J. L. Semeter, M. Nicolls, J. Labelle, and M. Broughton, On the localization of auroral Langmuir turbulence in thin layers, *J. Geophys. Res.*, submitted January 2013.

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